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IFAC-PapersOnLine 48-30 (2015) 529–534

Nonlinear Controller Design for Vehicle-to-Grid Systems with Output LCL Filters

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Abstract: This paper presents a nonlinear controller design for vehicle-to-grid (V2G) systems with LCL output filters. The V2G systems are modeled with LCL output filters in order to eliminate harmonics for improving power qualities and the nonlinear controller is designed based on the feedback linearization. The feasibility of using the appropriate feedback linearization approaches, either partial or exact, is also investigated through the feedback linearizability of V2G systems. In this paper, partial feedback linearization is used to design the controller with a capability of sharing both active and reactive power in V2G systems. The performance of the proposed controller controller is evaluated on a single-phase full-bridge converter-based V2G system with an LCL output filter and compared to that of without any filter. Simulation results clearly demonstrate the harmonic elimination capabilities of the proposed V2G structure with the proposed control scheme.

Keywords: Harmonic elimination, LCL filters, partial feedback linearization, power quality, V2G systems.

1. INTRODUCTION

Vehicle-to-grid (V2G) systems provide ancillary services to power networks by delivering power in case of emergency situations. In V2G systems, power electronic converters play a key role to supply electric power from plug-in electric vehicles (EVs) into the grids as the stored direct current (DC) power needs to convert into alternating current (AC) power. The power needs to be supplied in a manner that it can can match with the local demand during peak hours of overloaded distribution networks as well as in case of power blackouts or any other unpredictable event. Otherwise, power imbalances will occur into the grid which are prone to frequency and voltage stability problems. Moreover, power electronic converters are the main sources of harmonics which deteriorates the power quality. Therefore, it is essential to design V2G systems along with appropriate filters and control schemes in such a way that harmonics can easily be eliminated and desired power sharing can be maintained.

The power quality in V2G systems can be improved by using appropriate filters which can eliminate the harmonics. LCL filters are the most popular for grid-connected power electronic converters as these filters have the better attenuation capability of switching frequency harmonics and lower cost (Liu et al., 2009; Shen et al., 2010). An LCL filter is considered in (Mahmud et al., 2014b) for grid-connected solar photovoltaic (PV) systems to eliminate the harmonics and improve power quality. Though the impacts of V2G systems on power distribution networks have been well-studied (Galus et al., 2010; Papadopoulos et al., 2012; Fernandez et al., 2011; Das et al., 2014) but the power conversion technologies with different types of control techniques along with power quality issues are still at early stages.

Fuzzy logic controllers have been widely used for power conversion in V2G systems (Khayyam et al., 2012; Datta and Senjyu, 2012; Datta, 2014; Singhand et al., 2012; Thirugnanam et al., 2014). A fuzzy logic controller is used in (Datta and Senjyu, 2012) for V2G and PV applications to reduce active power fluctuations in tie-lines which in turn alleviates the frequency fluctuations. In (Datta, 2014), an aggregator has been designed based on the fuzzy logic control to maintain communication between the utilities and vehicles with an aim to control the grid frequency. However, the grid voltage is an important issue as this needs to be kept within a specified level (Mahmud et al., 2013). A V2G controller along with a charging station controller is proposed in (Singhand et al., 2012; Thirugnanam et al., 2014) by considering both voltage and frequency stability. The combination of adaptive neural network (ANN) and adaptive neural fuzzy inference system (ANFIS) is used in (Kaushal and Verma, 2014) to control both active and reactive power in V2G appli-

10.1016/j.ifacol.2015.12.434

cations where the control of reactive power ensures the voltage stability. These intelligent controllers (both fuzzy and ANN with ANFIS) provide good performance in terms of power sharing but the power quality issues have not been taken into account. Moreover, the fuzzy controllers have the limitations of capturing full dynamics of V2G systems and require more fine tuning before making them operational (Khayyam et al., 2012).

The shortcomings of intelligent controllers can be overcome by considering model-based controllers which require a dynamical model of V2G systems. A static model of V2G system is proposed in (Madawala and Thrimawithana, 2011) where a proportional integral (PI) controller is used for V2G applications. However, a dynamical model-based controller will provide better solution for V2G applications in term of power sharing and power quality enhancement. Since the major part of a V2G system includes a battery energy storage system (BESS), the mathematical model can be developed by incorporating a BESS model along with a grid-connected converter model. Based on this concept, the dynamical model of a V2G system has been developed in (Mahmud et al., 2014a) and a nonlinear feedback linearizing controller is designed for appropriate power (both active and reactive) sharing. However, the dynamics of the filter is not considered in the development of V2G systems.

This paper aims to design a feedback linearizing controller for V2G system by considering the dynamics of an LCL filter which is connected at the output of the inverter. The controller is designed based on the partial feedback linearization of V2G system models as the V2G system with an LCL filter is partially linearized which is also discussed in this paper. Finally the performance of the proposed controller is tested on a residential V2G applications to illustrate the effectiveness as compared to that of as presented in (Mahmud et al., 2014a) where no LCL filters are used.

2. MODELING OF V2G SYSTEMS WITH LCL FILTERS

A V2G system comprises a BESS, a voltage source converter (VSC), an LCL output filter, connecting lines, and a grid supply point as shown in Fig. 1. The battery model, used in this paper, is developed based on the electrochemical phenomenon as presented in (Ceraolo, 2000).

Based on the equivalent circuit diagram of a V2G system as shown in Fig. 1, the dynamical model of V2G system can be developed in a similar manner as presented in (Mahmud et al., 2014a) by simply applying the circuit theory. If Kirchhoff's current law (KCL) is applied at the battery of EV where the resistor and capacitor are connected together, then it can be written as

$$I_{dc} = I_1 + C_1 \frac{dV_{C_1}}{dt} \tag{1}$$

where $I_{dc} = mi_i$ is the output DC current of the battery, m represents the switching signal of the converter which is a function of modulation index and firing angle, I_1 is the current flowing through the resistor R_1, C_1 is the capacitor, V_{C_1} is the voltage across both C_1 and R_1 as they are connected in parallel which implies $V_{C_1} = I_1 R_1$ and simplifies equation (1) as

$$\frac{dI_1}{dt} = \frac{1}{\tau_1}(mi_i - I_1) \tag{2}$$

where $\tau_1 = R_1 C_1$ is the time constant of the battery. If Kirchhoff's voltage law (KVL) is applied at the first loop of the inverter output, the following relationship will be obtained:

$$\frac{di_i}{dt} = -\frac{R}{L_1} i_i + m\frac{v_{dc}}{L_1} - \frac{v_C}{L_1} \tag{3}$$

where R is the line resistance, i_i is the input current to the filter, and L_1 is the filter inductance. Again by applying KCL at the node where the filter capacitor C is connected, it can be written as

$$\frac{dv_C}{dt} = \frac{1}{C}(i_i - i_o) \tag{4}$$

where v_C is the voltage across the filter capacitor and i_o is the output current of the filter. Finally, by applying KVL at the output loop of the filter; it can be written as

$$\frac{di_o}{dt} = \frac{1}{L_2}(v_C - e) \tag{5}$$

where L_2 is the filter inductance and e is the grid voltage. Equations (2)–(5) represent an instantaneous model of the V2G system with an LCL filter. For the purpose of controller design, equations (2)–(5) need to be written in the dq-frame which can be done in the same way as presented in (Mahmud et al., 2014a) and in this case, the V2G system can be written as

$$\begin{aligned}
\dot{I}_1 &= \frac{1}{\tau_1}(M_d I_{id} + M_q I_{iq} - I_1) \\
\dot{I}_{id} &= -\frac{R}{L_1} I_{id} + \omega I_{iq} - \frac{v_{Cd}}{L_1} + \frac{v_{dc}}{L_1} M_d \\
\dot{I}_{iq} &= -\omega I_{id} - \frac{R}{L_1} I_{iq} - \frac{v_{Cq}}{L_1} + \frac{v_{dc}}{L_1} M_q \\
\dot{v}_{cd} &= \omega v_{cq} + \frac{1}{C}(I_{id} - I_{od}) \\
\dot{v}_{cq} &= -\omega v_{cd} + \frac{1}{C}(I_{iq} - I_{oq}) \\
\dot{I}_{od} &= \omega I_{oq} + \frac{1}{L_2}(v_{Cd} - E_d) \\
\dot{I}_{oq} &= -\omega I_{od} + \frac{1}{L_2}(v_{Cq} - E_q)
\end{aligned} \tag{6}$$

where the subscripts d and q denote the corresponding variables in d- and q-frame, respectively.

Since the paper is aimed to design a controller for the V2G system used in a residential area, the converter model is considered as a single-phase. In this case, the active and reactive power delivered into the grid can be written as

$$\begin{aligned} P &= E_q I_{oq} \\ Q &= E_q I_{od} \end{aligned} \tag{7}$$

Therefore, the injection of active and reactive power in V2G systems can be controlled by controlling I_{oq} and I_{od}, respectively. However, it is essential to analyze the feedback linearizability of V2G systems which is shown in the following section.

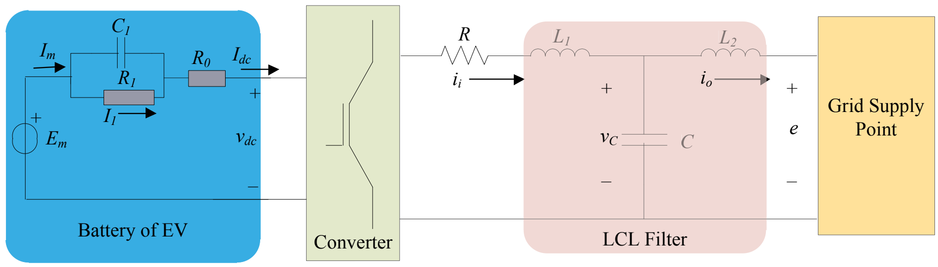

Fig. 1. V2G system with LCL filter

3. FEEDBACK LINEARIZABILITY OF V2G SYSTEMS

The V2G system model as represented by equation (6) has two inputs (M_d and M_q) and two outputs I_{oq} and I_{od}. Therefore, the mathematical model of V2G system can be represented by the following generalized equation of nonlinear systems:

$$\begin{aligned} \dot{x} &= f(x) + g_1(x)u_1 + g_2(x)u_2 \\ y_1 &= h_1(x) \\ y_2 &= h_2(x) \end{aligned} \tag{8}$$

where

$$x = \begin{bmatrix} I_1 \\ I_{id} \\ I_{iq} \\ v_{cd} \\ v_{cq} \\ I_{od} \\ I_{oq} \end{bmatrix}, \; f(x) = \begin{bmatrix} -\frac{1}{\tau_1} I_1 \\ -\frac{R}{L_1} I_{id} + \omega I_{iq} - \frac{v_{Cd}}{L_1} + \frac{v_{dc}}{L_1} M_d \\ -\omega I_{id} - \frac{R}{L_1} I_{iq} - \frac{v_{Cq}}{L_1} + \frac{v_{dc}}{L_1} M_q \\ \omega v_{cq} + \frac{1}{C}(I_{id} - I_{od}) \\ -\omega v_{cd} + \frac{1}{C}(I_{iq} - I_{oq}) \\ \omega I_{oq} + \frac{1}{L_2}(v_{Cd} - E_d) \\ -\omega I_{od} + \frac{1}{L_2}(v_{Cq} - E_q) \end{bmatrix},$$

$$g(x) = \begin{bmatrix} \frac{I_{id}}{\tau_1} & \frac{I_{iq}}{\tau_1} \\ \frac{v_{dc}}{L_1} & 0 \\ 0 & \frac{v_{dc}}{L_1} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \; u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} M_d \\ M_q \end{bmatrix}, \text{ and } y = \begin{bmatrix} I_{od} \\ I_{oq} \end{bmatrix}.$$

The feedback linearizability of nonlinear V2G systems determines whether the systems are exactly or partially linearized. The V2G systems will be partially linearized if the relative degree of the system is less than the order (which is seven for the considered model) of the system and exactly linearized if relative degree and order are equal to each other. The definition of relative degree can be seen in (Mahmud et al., 2012).

Since there are two outputs of the V2G system, it is essential to calculate the relative degree for each output and then sum up together to calculate the total relative degree of the system. To calculate the relative degree corresponding to the first output I_{od}, lets start with

$$L_g h_1 = L_g L_f^{1-1} I_{od} = 0 \tag{9}$$

Since $L_g L_f^{1-1} I_{od} = 0$, it is essential to proceed one step further. To do that, it is essential to obtain the following:

$$L_f^{2-1} I_{od} = \omega I_{oq} + \frac{1}{L_2}(v_{Cd} - E_d) \tag{10}$$

which in turn helps to calculate

$$L_g L_f h_1 = L_g L_f^{2-1} I_{od} = 0 \tag{11}$$

From equation (11), it can be seen that $L_g L_f^{2-1} I_{od} = 0$ which requires to move one step forward and in this case, we need to calculate

$$L_f^{3-1} I_{od} = \frac{1}{L_2 C} I_{id} - \mu I_{od} + \frac{2\omega}{L_2} v_{Cq} - \frac{\omega}{L_2} E_q \tag{12}$$

where

$$\mu = \left(\frac{1}{L_2 C} + \omega^2 \right)$$

and

$$L_g L_f^2 h_1 = L_g L_f^{3-1} I_{od} = \frac{v_{dc}}{L_1 L_2 C} = D \neq 0 \tag{13}$$

where is D is a constant. This implies that the relative degree corresponding to the first output function is three. At this point, the relative degree corresponding to the second output function needs to be determined. In order to determine the relative degree for the second output, we need to follow the same steps as presented above. At the beginning, we need to calculate $L_g L_f^{1-1} I_{od}$ which is also zero in this case. Therefore, lets start as follows:

$$L_f^{2-1} I_{oq} = -\omega I_{od} + \frac{1}{L_2}(v_{Cq} - E_q) \tag{14}$$

and

$$L_g L_f h_2 = L_g L_f^{2-1} I_{oq} = 0 \tag{15}$$

Since $L_g L_f^{2-1} I_{oq} = 0$, we need to move one step ahead, i.e.,

$$L_f^{3-1} I_{oq} = \frac{1}{L_2 C} I_{iq} - \mu I_{oq} - \frac{2\omega}{L_2} v_{Cd} + \frac{\omega}{L_2} E_d \tag{16}$$

and

$$L_g L_f^2 h_1 = L_g L_f^{3-1} I_{od} = \frac{v_{dc}}{L_1 L_2 C} = D \neq 0 \quad (17)$$

which implies that the relative degree corresponding to the second output is also three. Therefore, the total relative degree of the system is six which is less than than order of the system and the V2G system is said to be partially linearized. Since the V2G system is partially linearized, partial feedback linearization technique needs to be used to design the controller which is shown in the following section.

4. NONLINEAR CONTROLLER DESIGN FOR V2G SYSTEMS WITH LCL FILTERS

The design of partial feedback linearizing controller for V2G system with LCL filters requires to follow some steps such as nonlinear coordinate transformation, stability analysis of internal dynamics of V2G systems, and the derivation of final control law. These steps are discussed in the following:

- **Step 1:** Nonlinear coordinate transformation for obtaining partially linearized of V2G systems

From Section 3, it can be seen that the relative degree of the V2G system is six whereas the order of the system is seven which means that the seventh order system will be transformed into a sixth order system. Therefore, six new coordinates will be obtained from nonlinear coordinate transformation which can be written as

$$\begin{aligned}
\widetilde{z}_1 &= L_f^0 h_1 = I_{od} \\
\widetilde{z}_2 &= L_f^1 h_1 = \omega I_{oq} + \frac{1}{L_2}(v_{Cd} - E_d) \\
\widetilde{z}_3 &= L_f^2 h_1 = \frac{\omega}{L_2 C} I_{id} - \mu I_{od} + \frac{2\omega}{L_2} v_{Cq} - \frac{\omega}{L_2} E_q \\
\widetilde{z}_4 &= L_f^0 h_2 = I_{oq} \\
\widetilde{z}_5 &= L_f^1 h_2 = -\omega I_{od} + \frac{1}{L_2}(v_{Cq} - E_q) \\
\widetilde{z}_6 &= L_f^2 h_2 = \frac{1}{L_2 C} I_{iq} - \mu I_{oq} - \frac{2\omega}{L_2} v_{Cd} + \frac{\omega}{L_2} E_d
\end{aligned} \quad (18)$$

Using the nonlinear coordinate transformation as represented by equation (18), the following feedback linearized V2G system can be obtained:

$$\begin{aligned}
\dot{\widetilde{z}}_1 &= \widetilde{z}_2 \\
\dot{\widetilde{z}}_2 &= \widetilde{z}_3 \\
\dot{\widetilde{z}}_3 &= \widetilde{v}_1 \\
\dot{\widetilde{z}}_4 &= \widetilde{z}_5 \\
\dot{\widetilde{z}}_5 &= \widetilde{z}_6 \\
\dot{\widetilde{z}}_6 &= \widetilde{v}_2
\end{aligned} \quad (19)$$

with

$$\begin{aligned}
\widetilde{v}_1 &= L_f^3 h_1 + L_g L_f^2 h_1 M_d \\
&= -\alpha I_{id} + \beta I_{iq} - \gamma v_{Cd} - \eta I_{oq} + \frac{\gamma}{L_2} E_d + D M_d \\
\widetilde{v}_2 &= L_f^3 h_2 + L_g L_f^2 h_2 M_q \\
&= -\beta I_{id} - \alpha I_{iq} - \gamma v_{Cq} + \eta I_{od} + \frac{\gamma}{L_2} E_q + D M_q
\end{aligned} \quad (20)$$

where $\widetilde{v}_1$ and $\widetilde{v}_2$ are linear control laws which can be obtained by using any linear technique; α, β, γ, and η are are the constant and function of V2G system parameters which can be written as

$$\begin{aligned}
\alpha &= \frac{R}{L_1 L_2 C} \\
\beta &= \frac{3\omega}{L_2 C} \\
\gamma &= \frac{1}{L_1 L_2 C} + \frac{\mu}{L_2} + \frac{2\omega^2}{L_2} \\
\eta &= \mu\omega + \frac{2\omega}{L_2 C}
\end{aligned}$$

The original control laws (M_d and M_q) of the V2G system can be derived from equation (20). Before obtaining the original control laws, the internal dynamics of the V2G systems, which do not transform through feedback linearization, need to be analyzed and this has been discussed in the following steps.

- **Step 2:** Analysis of internal dynamics of V2G systems

Since the V2G system is transformed into a sixth order system, there will be only one remaining dynamic equation whose characteristics need to be investigated. The desired performance of the transformed dynamics is ensured with the linear controllers where the linear control laws are chosen as

$$\lim_{t\to\infty} h_i(x) \to 0$$

which means that the transformed states become zero as the time is increased, i.e., $\widetilde{z}_i \to 0$ with $i = 1, 2, \cdots, 6$ as $t \to \infty$. In order to obtain the remaining dynamic equation, the nonlinear coordinate transformation ($\hat{z} = \hat{\phi}(x)$) needs to be selected in a manner that it satisfies the following condition (Lu et al., 2001):

$$L_g \hat{\phi}(x) = 0 \quad (21)$$

The condition as represented by equation (21) will be satisfied for the considered V2G system, if the following nonlinear coordinate transformation is chosen:

$$\hat{\phi}(x) = \hat{z} = \frac{1}{2} L_2 I_{od}^2 + \frac{1}{2} L_2 I_{oq}^2 \quad (22)$$

With this nonlinear coordinate transformation, the remaining dynamic of V2G system can be written as follows:

$$\dot{\hat{z}} = L_f \hat{\phi}(x) = L_2 I_{od} f_6 + L_2 I_{oq} f_7 \quad (23)$$

As Since $I_{od} = \widetilde{z}_1$ and $I_{oq} = \widetilde{z}_4$, equation (23) can be written as

$$\dot{\hat{z}} = L_2 \widetilde{z}_1 f_6 + L_2 \widetilde{z}_4 f_7 \quad (24)$$

Since $\widetilde{z}_i \to 0$ with $i = 1, 2, \cdots, 6$; equation (24) can be simplified as

$$\dot{\hat{z}} = 0 \quad (25)$$

From equation (25), it can be seen that the internal dynamic of the V2G system with an LCL filter is zero and this is different from to that as presented in (Mahmud et al., 2014a). For the considered V2G system, the internal dynamic does not have any effect on the overall stability and thus, partial feedback linearizing control laws can be designed and implemented for this system which is shown in the following step.

- **Step 3:** Formulation of partial feedback linearizing control laws

Since the internal dynamic of the V2G system with an LCL filter does not have any affect, the original control law in dq-frame (M_d and M_q) can be obtained from equation (20) as

$$\begin{aligned} M_d &= \frac{1}{D}\left(\widetilde{v}_1 + \alpha I_{id} - \beta I_{iq} + \gamma v_{Cd} + \eta I_{oq} - \frac{\gamma}{L_2} E_d\right) \\ M_q &= \frac{1}{D}\left(\widetilde{v}_2 + \beta I_{id} + \alpha I_{iq} + \gamma v_{Cq} - \eta I_{od} - \frac{\gamma}{L_2} E_q\right) \end{aligned} \quad (26)$$

Equation (26)represents the final control law for the V2G system with an LCL filter which has the capability of delivering both active and reactive power into the grid. Since $\widetilde{v}_1$ and $\widetilde{v}_2$ are linear control inputs and can be determined using any linear techniques, PI controllers can be used to achieve the desired control objectives which can be obtained as follows

$$\begin{aligned} \widetilde{v}_1 &= k_{1p}(I_{odref} - I_{od}) + k_{1i}\int_0^t (I_{odref} - I_{od})dt \\ \widetilde{v}_2 &= k_{2p}(I_{oqref} - I_{oq}) + k_{2i}\int_0^t (I_{oqref} - I_{oq})dt \end{aligned} \quad (27)$$

The gains have been selected arbitrarily as a function of the reference values and in this paper, the gains are used as

$$k_{1p} = 2I_{odref},\ k_{1i} = I_{odref}^2,\ k_{2p} = 2I_{oqref},\ k_{2i} = I_{oqref}^2$$

With the designed controller, the performance of a V2G system in residential applications is evaluated in the following section.

5. SIMULATION RESULTS

The proposed V2G structure is considered for a residential application where the key objective is to deliver appropriate active and reactive power sharing into the grid supply point with high power quality. The batteries of EVs need to maintain a minimum state of charge (SOC) for delivering the power into the grid which can be calculated in a similar manner as presented in (Mahmud et al., 2014a; Singhand et al., 2012).

In this paper, it is assumed that the residential area consists of 15 PHEVs where each EV has a battery capacity of 4.4 kWh and these EVs are connected to the grid in order to supply a load of 5 KVA. The performance of the controller is evaluated in terms of delivering active and reactive power without any harmonic. When the consumers consume only active power, the controller needs to act in such a way that the V2G system can supply only active power. In this case, the voltage and current will be in phase with each other and 5 kW power will be delivered from the batteries of the V2G system. If the grid voltage is 220 V, the output current will be 22.72 A. Though the output current with the designed controller does not contain any harmonic as shown in Fig. 3 but the current with the same controller for the V2G system without an LCL filter as presented in (Mahmud et al., 2014a) contains some harmonics which can be seen in Fig. 2. The designed controller will perform in a similar way for all other operating conditions as it is designed in a manner that the linearization of the V2G system with an LCL filter is independent of operating conditions.

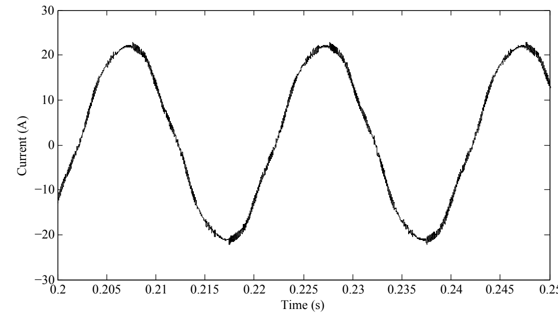

Fig. 2. Grid current at unity power factor for V2G system without LCL filter

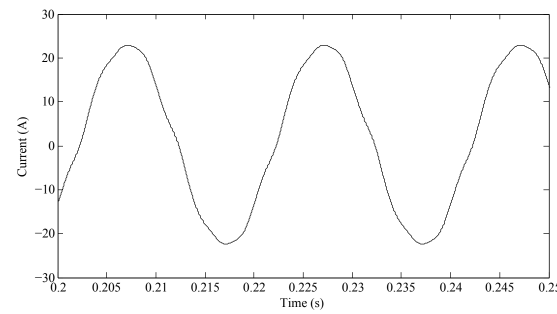

Fig. 3. Grid current at unity power factor for V2G system with LCL filter

6. CONCLUSIONS

A partial feedback linearizing controller has been designed for a V2G system with an output LCL filter where the dynamical model has also been developed for similar structures. The partial feedback linearizability of the whole V2G system determines the applicability of the proposed control scheme. Simulation results clearly indicate the superiority of the designed scheme over the existing one where the system model was mainly developed without any filter. Simulation results also reflect the harmonic rejection capability of the proposed V2G system structure along with the designed control scheme. The designed controller enhances the power quality in a much better way as compared to the existing controller. Since feedback linearization is sensitive to the variations in system parameters, future works will consider these parameter variations into the controller design.

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Appendix A. SYSTEM PARAMETERS

Battery Parameters:
R_1=0.4 mΩ, τ_1=7200 s, R_0=2 mΩ

Grid Parameters:
Grid voltage (rms)=220 V, Frequency=50 Hz, R=0.1 Ω, L=10 mH